RESEARCH BULLETIN 669 JULY, 1958
UNIVERSITY OF MISSOURI COLLEGE OF AGRICULTURE
AGRICULTURAL EXPERIMENT STATION
J. H. LONGWELL, *Director*

Excess Manganese Nutrition of Ornamental Plants

GERALD D. COORTS

(Publication authorized July 25, 1958)

COLUMBIA, MISSOURI

CONTENTS

INTRODUCTION 3

REVIEW OF LITERATURE 3

- Soil Manganese 4
- Fe:Mn Relations 5
- Chelated Iron 6
- Symptomatology 6
- Control 7

MATERIALS AND METHODS 7

- Nutrient Solutions 8
- Soil Culture 8
- Analytical Procedure 8

EXPERIMENTAL RESULTS 9

- Symptomatology 9
- Manganese Concentration in Plant Tissue 12
- Effect of Various Deficient Elements Upon Manganese Toxicity 14
- Effect of Fe:Mn Ratios Upon Manganese Toxicity 17
- Effect of Calcium on Manganese Toxicity in Soil Culture 20
- Effect of Iron on Manganese Toxicity in Soil Culture 22

DISCUSSION AND PRACTICAL APPLICATION 24

- Symptomatology 24
- Manganese Concentration in Plant Tissue 25
- Effect of Various Deficient Elements upon Manganese Toxicity 26
- Effect of Fe:Mn Ratios upon Manganese Toxicity 27
- Effect of Calcium on Manganese Toxicity in Soil Culture 28
- Effect of Iron on Manganese Toxicity in Soil Culture 29

SUMMARY AND CONCLUSIONS 30

BIBLIOGRAPHY 31

APPENDIX TABLES 33

COLOR PLATES 18-19

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr. Marlin N. Rogers for his excellent advice and criticism and under whose direction this problem was carried out. He also wishes to express his sincere appreciation and thanks to Dr. A. D. Hibbard and Dr. Jacob Levitt for their encouragement and criticism of the thesis, to Prof. J. E. Smith, Jr. and Mr. Joe Gorgan for their invaluable advice and criticisms, and to Dr. E. E. Pickett for performing the spectrographic analyses.

Excess Manganese Nutrition of Ornamental Plants

GERALD D. COORTS

INTRODUCTION

Manganese is an essential micronutrient for the normal metabolism of plants. It usually occurs in soils in amounts sufficient to meet plant requirements. In an investigation of manganese in some Missouri soils, Dinius (7) found the total manganese content of ten soil types to vary from 0.10 percent in the Lebanon to 0.03 percent in the Gerald.

It is known that manganese is taken up by plants somewhat in proportion to the amounts available in the soil. However, depending on soil and climatic conditions, manganese may be present in chemical compounds which are unavailable to the plant or are so readily available that toxic amounts are absorbed.

Several commercial flower growers in Missouri have reported what appeared to be manganese toxicity. Symptoms occurred either on soils known to be naturally high in manganese or following over-application of trace element fertilizers. Characteristic symptoms of manganese toxicity have been observed in plants at different manganese concentrations. The concentration at which toxicity symptoms appear varies with plant species and environment.

The object of this study was to describe the symptomatology of manganese toxicity on selected ornamental plants, its accumulation in plant tissue, its interactions with other elements and to explore possible means of control.

REVIEW OF LITERATURE

McHargue (25) in 1922 established that manganese is essential as a micronutrient element for green plants. Many investigators have secured data which shows that this element has a definite function in the plant metabolism. In summarizing research to 1952, Mulder and Gerretson (30) state:

> "There is increasing evidence that Mn plays an important role in the photosynthetic apparatus of green plants and together with Fe controls the oxidation-reduction potentials in the cells during illumination and in the dark."

Manganese toxicity had been reported long before manganese was found to be an essential plant nutrient. One of the first reports of toxicity was by Loew and Sawa (19) in 1902. They found that leaves lost their turgor and dried up,

and there was no trace of new rootlets when toxic quantities of manganese were present. Their work was corroborated by Brenchley's (4) report in 1914 that manganese in strong concentrations is toxic to higher plants.

Soil Manganese

Manganese exists in the soil in various states of oxidation having widely different solubilities. Leeper (17) proposed the hypothesis of the existence of soil manganese in a dynamic oxidation reduction equilibrium, which may be expressed as follows: (a) water-soluble $Mn^{++} \rightleftarrows$ (b) exchangeable $Mn^{++} \rightleftarrows$ (c) easily reducible $MnO_2 \rightleftarrows$ (d) relatively inert manganic oxides.

Later, Leeper (18) classified the forms of soil manganese as follows:

1. *Bivalent manganese* (Mn^{+2}) which may exist as either an ion in the soil solution or in exchangeable or non-exchangeable forms.
2. *Trivalent manganese* (Mn^{+3}) which may exist as $Mn_2O_3 \cdot H_2O$ or as $Mn(OH)_3$.
3. *Tetravalent manganese* (Mn^{+4}) which exists as MnO_2.
4. *Intermediate compounds containing manganese* in two valent states eg. Mn_3O_4.

Under alkaline conditions the bivalent form of manganese is readily oxidized to a higher valency state. Acid conditions favor reduction of manganic manganese to the manganous form.

The work of Hale and Heintze (12), Lohnis (21), Millikan (27), Morris (28), and McCool (23) have shown that toxic manganese levels exist in soils under certain conditions. Factors which affect manganese availability are changes in temperature, changes in water saturation, changes in pH and changes in oxidation-reduction conditions.

A study of the effects of steam sterilization of soil upon plant growth and upon the availability of manganese in soils was conducted by Fujimoto and Sherman (10), Forsee (9), McCool (23), and Ozaki (31). They found that steam sterilization of soils increased the exchangeable manganese considerably. Sterilizing soils also resulted in an increased uptake of manganese by plants.

Lohnis (20) observed that at high temperatures bean plants tolerated a high manganese content in the foliage without visibile injury. The recent work of Mederski and Wilson (26) on manganese absorption as influenced by soil temperature and soil moisture also gave evidence that environment may influence the absorption of manganese.

Light is another environmental condition which affects manganese absorption by plants. Several workers have investigated the effect of light intensity on plants growing with different manganese concentrations. Hopkins *et al.* (15) and McCool (24) found that injury to plants due to too much manganese was greater in more intense light.

Soil acidity is an important factor in the occurrence of manganese in its various forms. According to Willis (44), the influence of soil pH on the solubility of manganese is very marked. Acid conditions in the soil favor the formation of

divalent manganese, which is available to plants and may be determined as an exchangeable ion. As the pH of soils increases there is a tendency for the divalent manganese to be oxidized to the higher oxides, which are insoluble and unavailable to plants. High manganese content of acid soils is apt to cause injury to plants, according to Hale and Heintze (12). Wallace and Hewitt (42) state that on acid soils manganese may be toxic to many plants.

The availability of manganese is also affected by changes in oxidation-reduction conditions. Piper (32) states that temporary waterlogging promotes reducing conditions in the soil. Sherman, McHargue, and Hodgkiss (35) observed that manganese-deficient soils have a high capacity for the oxidation of added manganese.

Fe:Mn Relations

There are many references in the literature to the importance of iron and manganese ratios and their relation to plant nutrition. Somers and Shive (38) conclude from their research:

> "Iron and Mn are definitely interrelated in their metabolic functions, the biological effectiveness of the one being determined by the proportionate presence of the other."

They found in nutrient substrates that an Fe:Mn ratio of around 2:1 produced the best growth and development of plants regardless of the total concentrations of these two elements. The symptoms of Mn toxicity corresponded with those of Fe deficiency, and symptoms of Fe toxicity corresponded with those of Mn deficiency.

Twyman (40) reports that in certain cases iron chlorosis is correlated with a high manganese concentration in the plant and in the nutrient medium. He concluded that iron chlorosis can be cured by reducing the manganese level in the substrate or by raising the iron content of the plants by spraying or by application of iron salts to the soil or culture medium.

Morris and Pierce (29) state further that the beneficial effect of iron in reducing manganese toxicity was due to a decrease in manganese absorbed by the plant rather than an increase in iron absorption.

In apparent contradiction, Carlson and Olson (5) evaluated the importance of the ratio of iron to manganese in the nutrient medium as a factor in the occurrence of chlorosis. After studying chlorophyll analyses and yields, they concluded that iron-manganese ratios were not important at high and low iron levels, but were important only at the medium level. There was no reciprocal relationship existing between iron and manganese in plant sap or dried tops.

Kuykendall in the symposium on the use of metal chelates (41) has fairly well established that large soil accumulations of heavy metals such as manganese interfere with the normal absorption of iron by plant roots. He further states that when metallic manganese and iron ions are made equally accessible to roots, most plants will absorb manganese in preference to iron. This causes what has

been variously called manganese excess or iron deficiency.

Chelated Iron

The biological effectiveness of manganese or iron is determined by the proportionate presence of the other. Normally, high concentrations of soluble manganese in plant tissue are associated with low concentrations of soluble iron. Somers and Shive (38) suggest that the oxidation of ferrous to ferric ions by active manganese results in the inactivation and precipitation of iron in the form of ferric organic complexes.

Iron deficiency which causes chlorosis in plants can be corrected or controlled by the use of chelated iron compounds. The function of iron chelates is explained in a symposium edited by Arthur Wallace (41). The soluble iron chelate is absorbed by the root and both iron and chelate move to the leaves. Once in the leaf, the iron is removed from the chelate and functions in the metabolism of the leaf. The use of an iron chelate thereby tends to lessen manganese toxicity.

Wallace further states in the symposium that plants can tolerate an intermittent supply of nitrogen, phosphorous, or potassium, but not of iron. Frequent and repeated applications of iron in inorganic form are necessary to give a continuously available supply to the plant. Even with chelated iron as a source, it is difficult to maintain a continuous supply of iron for a long time with a single application.

Weinstein *et al.* (43) using a split-root technique with sunflower plants, found that with ferrous sulfate in one compartment and disodium ethylenediamine tetraacetate in the other, plants had a high iron content, made good growth, and did not show chlorosis, while those grown with no added chelate were chlorotic and smaller. Disodium ethylenediamine tetraacetate or a closely related decomposition product appeared to be readily absorbed through the roots. It chelated the inactivated iron and transported it to the site of enzyme synthesis.

Symptomatology

Many workers have reported the manganese levels in plant tissue which result in toxicity symptoms. One of the first reports was by Loew and Sawa (19) who reported that the leaves of barley plants faded to yellow and then turned brown when grown in solution containing 1000 parts per million of manganese sulfate. These investigators also found that barley became chlorotic and the roots turned brown in solutions containing only small quantities of manganese. Brenchley (4) corroborated the work of Loew and Sawa and added that at an early stage in growth, the lower leaves of the plants receiving the most manganese began to be flecked with brown spots. Later, Deatrick (6) reported that the yellow or chlorotic leaves of plants grown at excess manganese levels contained more manganese than green ones.

Many workers have analyzed plant tissue for manganese content. Using

steamed soils, Sherman and Fujimoto (36) reported that manganese toxicity symptoms occurred in carrot tops containing 3800 parts per million manganese and in lettuce containing 3000 parts per million manganese.

Lohnis (21) reported 1080 parts per million manganese in injured alfalfa and 1300 parts per million manganese in chlorotic red clover. In an earlier paper (20), he reported that in healthy young bean leaves manganese ranged from 40 to 940 parts per million and in affected leaves from 1104 to 4261 parts per million. In a more recent paper, Baxter (2) reported that peach leaves did not show abnormal symptoms when the total manganese content was below 600 parts per million. He also noted that the affected leaves showed an interveinal chlorosis similar to manganese deficiency symptoms, but actually contained excessive amounts of manganese.

Control

Little work has been done to establish a reliable method for controlling manganese toxicity. Several workers report that lime is effective. Albrecht and Smith (1) state that when limestone was mixed through the soil to modify its reaction, both the concentration and total content of manganese in the crops were decreased as the application to the soil and the consumption of calcium increased. However, when the application was confined to the surface layer, in an attempt to increase consumption of the calcium, there was a reverse effect on manganese, so that the concentration and the total manganese content were increased.

Hewitt (13) also reported that increasing the calcium supply in soil reduced the severity of manganese toxicity symptoms and also reduced the accumulation of manganese in the plant tissue. In contradiction, Morris and Pierce (29) found that increasing the calcium concentration of nutrient solution did not reduce manganese toxicity. This apparent contradiction might be attributed to the difference in growing media.

MATERIALS AND METHODS

Calendulas, carnations, chrysanthemums, poinsettias, roses, snapdragons, and stocks were grown as test plants. A stock bed of "Bonnafon Deluxe" chrysanthemum was planted and used as a source of cuttings for the problem. The variety "Mamie" carnation was obtained as rooted cuttings from a St. Louis grower. Varieties of roses and poinsettias used were "Better Times" and "Barbara Ecke Supreme" respectively. Cuttings of these plants were rooted in sand under intermittent mist. Other plants grown were: calendula, "Ball Improved Long Orange"; snapdragon, "Christina"; and stock, "Ball's Supreme No. 22".

The seed-propagated plants were germinated in vermiculite and transplanted either into 2¼-inch peat pots containing soil, or clay pots containing washed river sand. All plants were grown to maturity in new 4-inch clay pots with

saucers, unless stated otherwise.

Test plants were grown in both nutrient solution and soil under temperatures considered normal for the plant, *i.e.,* rose house (night temperature of 62° F) or carnation house (night temperature of 50° F).

Nutrient Solutions

Since soils are an extremely complex body and are continuously changing, nutrient solution cultures were used in part of the work. Hoagland and Arnon (14) nutrient solution was used for all plants growing under nutrient culture. The nutrients were prepared individually as concentrated stock solutions and diluted to final concentrations in gallon pyrex containers. The water used in preparing stock solutions and culture solutions was single-distilled. All plants were fed approximately 100 cc. of nutrient solution per day as a drench, thereby giving the solid aggregate culture a periodic irrigation. There is no need for mechanical aeration of this type of nutrient culture.

The nutrient stock solutions were prepared using reagent grade compounds. Iron was added as equal parts iron citrate and iron tartrate, unless otherwise specified. Manganese was added as manganese sulfate tetrahydrate.

The levels of manganese used in the nutrient culture experiments were 1, 2½, 5, 10, 25, 50, 100, and 200 parts per million respectively. These were chosen to range from adequate through toxic based on experimental evidence.

Soil Culture

Plants were grown in pots in soil culture for comparison with plants grown in nutrient culture to give a general indication of the plant reaction to manganese toxicity under field conditions.

The normal greenhouse potting mixture of two parts soil, two parts leaf mold, and one part sand was used unless otherwise specified. All soil was steam sterilized and allowed to stand in the soil bin for several weeks prior to use.

Manganese was added to the soil as manganese sulfate, fertilizer grade, and thoroughly mixed. The levels of manganese used in the experiments were 1, 2, 3, 4, 6, 8, and 10 grams per four-inch pot.

Plants were watered as needed, taking care not to over water and leach the soil. The plants were given no additional fertilizer during the growing period.

All plants were grown under normal day length, except for chrysanthemum, which was grown according to the commercial schedule for flower production in off-season periods.

Analytical Procedure

Plants showing distinct symptoms were harvested after being grown for 6 to 8 weeks by cutting them off at ground level. They were then placed in a forced draft dryer at 65° C. After drying, the plant material was ground in a Wiley mill with a fine screen and placed in glass containers. The samples were

sent to the spectrographic lab where they were wet-ashed for manganese determination by the periodate method (34).

Soil samples were taken before and after each soil culture experiment. The air-dry soil was analyzed for available manganese by the periodate method, using normal ammonium acetate as extracting reagent. The pH of the soil solution was measured by use of the glass electrode. Other elements were analyzed by the Missouri soil test procedure (11).

EXPERIMENTAL RESULTS

It should be pointed out that the separate experiments were not performed under identical conditions. The physiological ages of the plants were not exactly the same, nor were the conditions of humidity, light and temperature, since the experiments were carried out at different seasons in a greenhouse where these factors could be controlled to only a limited extent.

Symptomatology

This group of experiments was designed to produce and identify foliar symptoms associated with toxic levels of manganese in both nutrient solution and soil culture.

Manganese toxicity was observed on calendula plants grown in solution culture 10 to 14 days after excess manganese had been added. The visible symptoms were a reduced growth rate and a necrosis of the leaf midrib with scattered necrotic spots on the lower leaves. In high concentrations the leaves were very distorted. At sub-toxic levels of manganese it was noted that the leaves were very brittle. Similar symptoms were obtained in soil culture and may be observed in Figure 1.

Carnations grown with excess manganese showed toxicity symptoms slowly. Symptoms were apparent approximately two months after the treatment was started. The visible symptoms were a tip burn of the leaves and necrotic spots. A reduced rate of growth and distorted leaves were observed at high manganese concentrations. The same general symptoms were observed in soil culture except that leaf tip-burn was more severe. (See Figure 2.)

Chrysanthemums were markedly affected by small amounts of manganese above the requirements of the plant. The symptoms expressed were a terminal, interveinal chlorosis with a suppression of new growth at high levels. These were similar for both nutrient solution and soil cultures. (See Figures 3 and 4.)

Poinsettias apparently tolerate high amounts of manganese up to 100 ppm in nutrient solution. At higher levels the typical foliar symptom was a brown necrotic spotting appearing first on the older leaves and later in the younger leaves. There was a marked stimulation in growth when small amounts of manganese were added. Only at the highest levels tested was there a decrease in terminal growth.

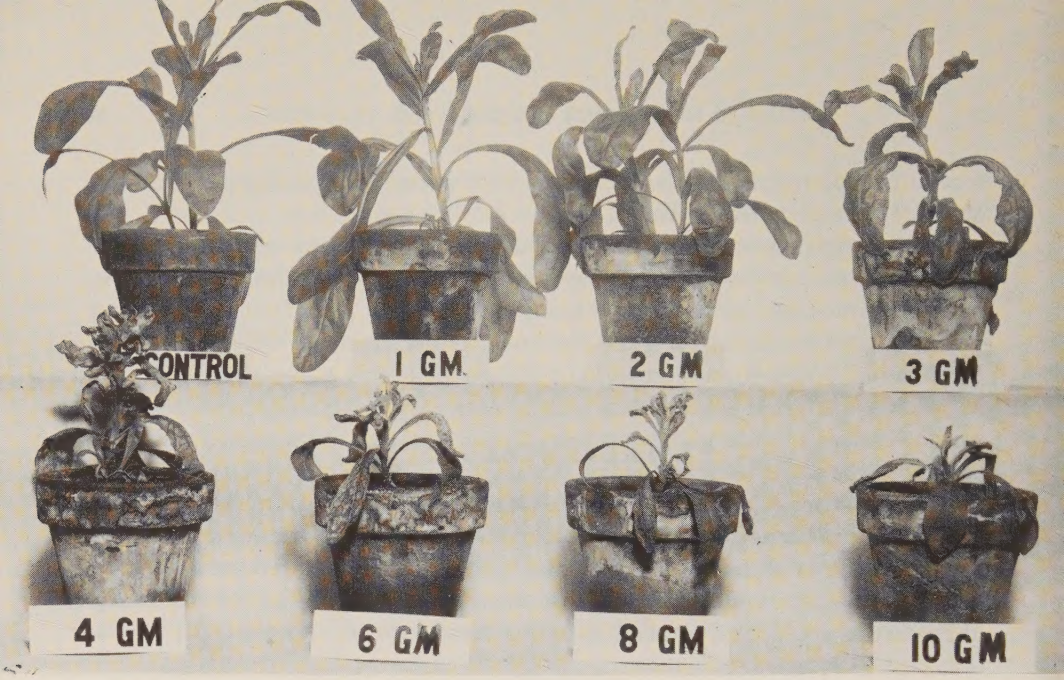

Fig. 1—Symptom expression of calendula grown in soil at increasing manganese levels.

Fig. 2—Symptom expression of carnation grown in soil at increasing manganese levels.

Fig. 3—Comparison of symptom expression showing interveinal chlorosis in chrysanthemum. The leaf on the left is from the control, with leaves from plants grown in increasing manganese concentrations to the right.

Roses were grown in both nutrient solution and soil culture. They also have a high tolerance for added manganese. Symptoms expressed by roses were terminal chlorosis, small black spots on the older mature, green leaves, and suppression of terminal growth. The chlorosis was found to be scattered throughout the treatments at random, and could be eliminated by a soil treatment of iron. Thus, the chlorosis would seem to mask the true symptoms of manganese toxicity which would appear as small black spots on the older mature, green leaves.

Snapdragons are quite susceptible to excess manganese. When these plants were grown in soil culture, all levels tested showed a decrease in terminal growth over the control. Symptom expression was an overall chlorosis with necrotic

Fig. 4—Symptom expression of chrysanthemum grown in soil at increasing manganese levels.

spots and browning of the leaf midrib. (See Figure 5.)

Stocks grown in nutrient solution culture in vermiculite were highly tolerant of excess amounts of manganese. When grown in solutions containing 50 ppm manganese, the plants exhibited symptoms of necrotic spots on the older, lower leaves. This symptom expression evolved slowly. (See Figure 6)

Manganese Concentration in Plant Tissue

Plants grown in nutrient solution and soil culture were harvested at the completion of each experiment and prepared for laboratory analysis of plant manganese. The results of these analyses are shown in Tables 1 and 2.

Table 3 shows extractable manganese in soils prepared for growing the test plants and the amount of manganese in the soil at the time of harvest.

Generally, the amounts of manganese in plant tops increased with increasing amounts in the substrate. Plants such as chrysanthemums accumulate much more manganese than others growing under the same treatment.

Table 4 summarizes the manganese levels in nutrient solution and soil culture at which the first visible toxicity symptoms appeared in the test plants. The manganese concentration in the plant top is also listed for these levels.

Tolerant plants, such as roses, accumulate less manganese in the plant tissue than non-tolerant plants, such as calendulas. This is not always true. One would assume that a plant should exhibit toxicity symptoms at the same plant

Fig. 5—Symptom expression of snapdragon grown in soil at increasing manganese levels.

Fig. 6—Comparison of symptom expression showing necrotic spots in stocks. The leaf on the left is from the control, with leaves from plants grown in increasing manganese concentrations to the right.

concentration of manganese regardless of whether it is grown in nutrient solution or soil culture. Plants tolerant of excess manganese, such as carnations and roses, follow this trend more closely than do non-tolerant plants such as

TABLE 1 -- MANGANESE CONCENTRATION IN THE TOPS OF ORNAMENTAL PLANTS GROWN IN NUTRIENT SOLUTION AT VARIOUS LEVELS OF MANGANESE

Mn level in culture Sol'n	Calendula	Carnation	Chrysanthemum	Poinsettia	Rose	Stock
ppm	ppm	ppm	ppm	ppm	ppm	ppm
0	230	215	540	208	150	----
1	210	230	----	138	302	----
2 1/2	223	304	----	175	333	----
5	295	450	410	210	440	470
10	536	654	718	290	716	763
25	1225	1150	1470	710	1160	2500
50	2630	2075	2670	1325	1720	5500
100	4650	3380	4660	3440	3500	----
200	8370	5700	10800	5160	4570	----

TABLE 2 -- MANGANESE CONCENTRATION IN THE TOPS OF ORNAMENTAL PLANTS GROWN IN SOIL CULTURE AT VARIOUS LEVELS OF MANGANESE

$MnSO_4$ added to soil	Calendula	Carnation	Chrysanthemum	Rose	Snapdragon
Grams per 4" pot	ppm	ppm	ppm	ppm	ppm
0	830	448	235	900	1190
1	2450	1280	720	880	1900
2	4150	2320	1110	1225	7500
3	5200	4000	4470	1470	7250
4	6940	4810	5590	2740	7500
6	8100	6670	6780	2950	9500
8	9070	7450	9200	3450	7750
10	10400	8990	14000	4440	13000

TABLE 3 -- EXTRACTABLE MANGANESE IN SOIL SAMPLES PRIOR TO AND FOLLOWING GROWTH OF SNAPDRAGON

$MnSO_4$ added to soil	Extractable Manganese	
	prior to planting	at harvest
Grams per 4" pot	ppm	ppm
Control	185	119
1	659	386
2	853	612
3	1460	1150
4	1930	1390
6	2620	1830
8	3240	2270
10	4650	2620

calendula and chrysanthemum.

Effect of Various Deficient Elements Upon Manganese Toxicity

Chrysanthemum cuttings which had been rooted under mist in sharp sand were transplanted to four-inch clay pots filled with white silica sand. The cuttings were fed half-strength nutrient solution for a week following transplanting

TABLE 4 -- MANGANESE CONCENTRATION IN PLANT AND SUBSTRATE AT WHICH FIRST VISIBLE SYMPTOMS OF MANGANESE TOXICITY APPEARED.

Ornamental	Soil Culture		Solution Culture	
	Soil Conc.	Plant Conc.	Solution Conc.	Plant Conc.
	Grams per 4" pot	ppm	ppm	ppm
Calendula	3	5200	50	2630
Carnation	4	4810	200	5700
Chrysanthemum	4	5590	50	2670
Poinsettia	-	----	100	3440
Rose	6	2950	50	1720
Snapdragon	1	1900	---	----
Stock	-	----	50	5500

and full strength nutrient solution for the remainder of their growing period. Various nutrient treatments were carried out comparing single-nutrient deficient solutions with the same deficient nutrient solution containing 100 ppm excess manganese. These deficient nutrient solutions were prepared as recommended by Hoagland and Arnon (14).

Results of this experiment showed a highly significant decrease in growth of chrysanthemum plants in all treatments when compared with the control. The fresh weights as recorded and their statistical analyses are shown in Appendix Table A and Figure 7. Added manganese decreased plant growth in all treatments when compared to the control except in the case of the magnesium deficient treatment, which showed an increase. (See Figure 8)

The concentration of minerals in chrysanthemum plant tops grown under various mineral deficiencies with and without excess manganese and with a complete solution is shown in Table 5. All deficiency treatments except magnesium and iron resulted in an increased concentration of the various elements when the plant was grown with excess manganese.

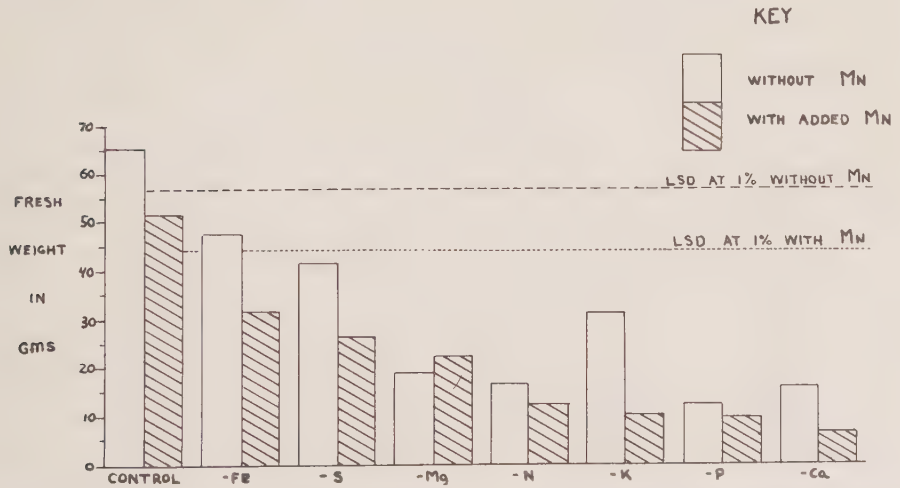

Fig. 7—Fresh weight of chrysanthemum grown in nutrient solution culture deficient in single elements with and without added manganese.

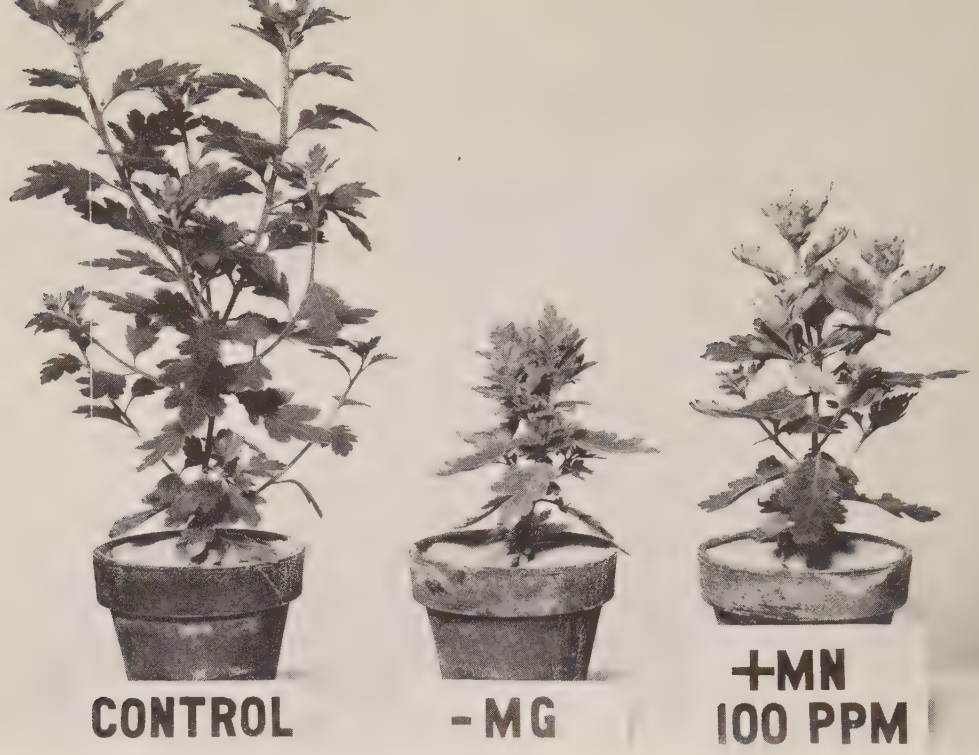

Fig. 8—Comparison of symptom expression of chrysanthemum when grown in solution containing 100 ppm added manganese and deficient in magnesium as compared to the control.

TABLE 5 -- CONCENTRATION OF MINERALS IN TOPS OF CHRYSANTHEMUM GROWN UNDER VARIOUS MINERAL DEFICIENCIES WITH AND WITHOUT EXCESS MANGANESE.

Treatment	N	P	K	Ca	Mg	S	Fe	Mn
	%	%	%	%	%	%	ppm	ppm
Control (Complete Sol'n)	2.02	0.408	3.20	1.29	0.379	0.217	2550	204
Control + Mn[a]	2.48	.535	4.03	1.81	.816	.236	1730	6590
Minus Nitrogen	.83							214
Minus N + Mn	.85							2870
Minus Phosphorus		.115						129
Minus P + Mn		.150						2410
Minus Potassium			.535					172
Minus K + Mn			1.25					6240
Minus Calcium				.531				181
Minus Ca + Mn				.840				4720
Minus Magnesium					.216			1680
Minus Mg + Mn					.161			4370
Minus Sulphur						.231		195
Minus S + Mn						.321		6790
Minus Iron							595	170
Minus Fe + Mn							432	6675

[a]All treatments with added manganese had 100 ppm manganese.

Effect of Fe:Mn Ratios Upon Manganese Toxicity

Previous investigators (40) have reported that the ratio of iron to manganese in the nutrient medium is a factor in the occurrence of chlorosis associated with manganese toxicity. This experiment was carried out to verify the hypothesis that this chlorosis can be cured by raising the iron content of the plant.

Chrysanthemum cuttings which had been rooted under mist in sharp sand were transplanted to four-inch clay pots filled with vermiculite. The plants were fed nutrient solution daily with the various types of iron at two levels i.e., one and 100 ppm respectively. Iron sources[1] used were Sequestrene NaFe iron chelate, Sequestrene 330 Fe iron chelate, Greenz 26, and a mixture of equal parts iron citrate-tartrate. Manganese sulfate was used as the manganese source at two concentrations, *i.e.,* five and 100 ppm respectively. For comparative purposes, plants were grown as a control in nutrient solution containing one ppm iron and 0.5 ppm manganese. After the plants had grown for eight weeks, they were harvested and analyzed. Fresh weights were recorded and their statistical analyses are shown in Appendix Table B and Figure 9.

[1]Sequestrene NaFe (mono sodium ferric ethylenediamine tetraacetate) and Sequestrene 330 Fe (mono sodium ferric diethylenetriamine pentaacetate) used in these experiments were secured from the Geigy Chemical Corporation, Agricultural Chemicals Division, New York 8, New York. Greenz 26 (ammonium lignin sulfonate) used in these experiments was secured from the Crown Zellerbach Corporation, Chemical Products Division, Camas, Washington.

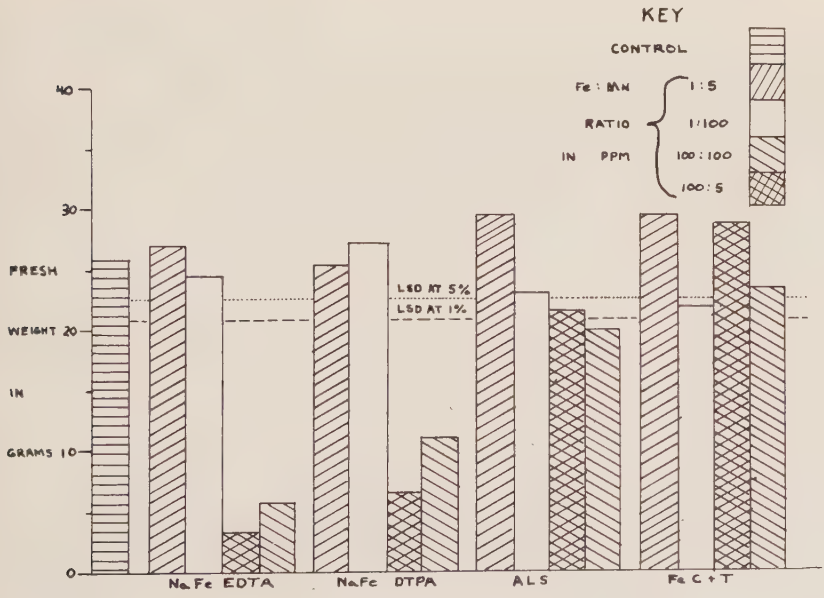

Fig. 9—Fresh weight of chrysanthemum grown with various iron sources using nutrient solution culture with two levels of iron and manganese combined to give four Fe:Mn ratios.

Section of mature calendula leaf showing necrosis of the midrib and scattered necrotic spots.

Section of mature rose leaflet showing small black spots attributed to manganese toxicity.

Comparison of symptom expression of manganese toxicity on poinsettia when grown in nutrient solution culture containing 100 ppm Mn and 200 ppm Mn as compared to the control plant on right. Top row of leaves taken high on the plant and bottom row low.

Comparison of symptom expression of manganese toxicity on carnation showing leaf tip-burn when grown in nutrient solution culture containing 200 ppm Mn as compared to the control plant on the left.

In all treatments using a chelated iron source at 100 ppm there was a highly significant decrease in growth over that of the control regardless of whether the manganese was at a high or low level in the nutrient solution. Conversely, the iron citrate-tartrate treatment at 100 ppm produced no significant difference in growth at either manganese level. However, a significant decrease in growth did occur at one ppm iron and 100 ppm manganese.

The concentration of iron and manganese in chrysanthemum plant tops grown with various iron sources at four Fe:Mn ratios is shown in Table 6. The

TABLE 6 -- IRON AND MANGANESE CONCENTRATION OF TOPS OF CHRYSANTHEMUM GROWN USING VARIOUS IRON SOURCES AT FOUR Fe:Mn RATIOS.

Fe:Mn Ratio	Iron	Manganese
	ppm	ppm
Control	418	273
NaFe EDTA		
1:5[a]	366	1770
1:100	4140	628
100:5	2280	1700
100:100	534	375
NaFe DTPA		
1:5	448	1750
1:100	2060	462
100:5	1460	2300
100:100	330	305
ALS		
1:5	435	1930
1:100	714	453
100:5	522	2170
100:100	428	300
Fe C. & T.		
1:5	364	2010
1:100	369	264
100:5	440	1750
100:100	438	134

[a]The Fe:Me ratios are stated in ppm used in the nutrient solution.

highest concentration of iron in the plant tops was found in the treatment with one ppm NaFe EDTA and 100 ppm manganese. High concentrations of iron were also found in the treatments with 100 ppm chelated iron and five ppm manganese. The iron citrate-tartrate treatment gave little difference between ratios. As to manganese content, all treatments containing five ppm manganese showed the highest concentration in the plant tissue regardless of the concentration of iron. One would normally expect that the treatments with 100 ppm manganese added would show the highest manganese concentration in the plant tissue.

Effect of Calcium on Manganese Toxicity in Soil Culture

Previous investigators (1) (13) indicated that the application of calcium to a

soil containing excess manganese will alleviate or prevent foliar symptoms of manganese toxicity. They indicate that the reduction in the severity of manganese toxicity in limed soils is accompanied by an increase in pH with a reduction in the level of exchangeable soil manganese. In this experiment, the effects of various calcium sources on the pH and level of soil manganese were studied to determine their interacting effects on plants.

Loess soil was obtained from the horticulture farm at New Franklin, Missouri, steam sterilized, and used a week later for potting. The soil was tested and the initial exchange capacity calculated to be 10.85 m.e. Calcium was added to the soil as either CaO, $CaSO_4$, or $CaCO_3$ at two base saturations and at two manganese levels. The base saturations were calculated at 75 and 90 percent and the levels of manganese in the soil were the natural level and an addition of 5 grams manganese sulfate per four-inch clay pot for the high level.

Calendulas which had been transplanted to 2¼-inch peat pots were potted in the respective treatments. After the plants had grown for ten weeks, they were harvested and analyzed. Fresh weights were recorded and statistically analyzed as shown in Appendix Table C and Figure 10.

This experiment showed no significant increase in growth in any treatment over that of the control.

Significant decreases in growth were obtained using CaO at 75 percent base saturation plus Mn and CaO alone at the 90 percent base saturation. $CaSO_4$ at 90 percent base saturation showed a highly significant decrease whether with or with-

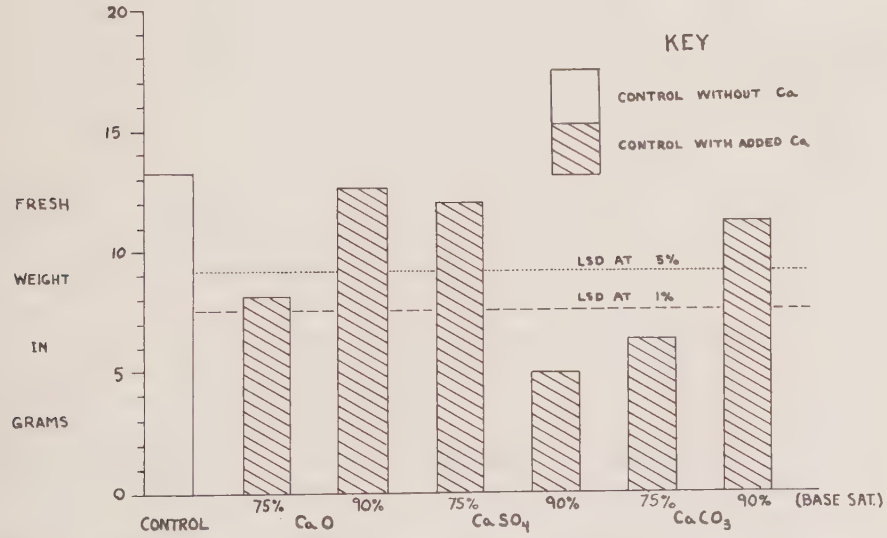

Fig. 10—Fresh weight of tops of calendula grown using various sources of calcium at two base saturations with added manganese at five gm $MnSO_4$ per four-inch pot of soil.

out added manganese. $CaCO_3$ at the 75 percent base saturation plus Mn also showed a highly significant decrease.

The concentration of calcium, iron and manganese in the plant tops varied with the treatments as shown in Table 7. The highest concentration of manganese in the plant tissue was found in the 75 percent $CaCO_3$ plus manganese treatment. The concentration of iron in the plant tissue was consistently higher in all treatments with added manganese except the control. Conversely, in the high manganese treatments, calcium concentration in the plant tissue was decreased to approximately half that of the treatments where manganese was not added.

TABLE 7 -- CALCIUM, IRON, AND MANGANESE CONCENTRATION OF TOPS OF CALENDULA PLANTS GROWN IN SOIL TREATED WITH VARIOUS CALCIUM SOURCES AT TWO BASE SATURATIONS WITH AND WITHOUT ADDED MANGANESE.

Treatment	Manganese	Iron	Calcium
	ppm	ppm	%
Control	3120	1210	3.42
Control + Mn[a]	8880	845	1.80
75% CaO	1590	761	3.37
75% CaO + Mn	9000	1800	1.92
90% CaO	934	570	3.35
90% CaO + Mn	9170	1390	1.79
75% $CaSO_4$	1100	1180	3.30
75% $CaSO_4$ + Mn	10000	1510	1.65
90% $CaSO_4$	872	1100	3.04
90% $CaSO_4$ + Mn	5100	1820	1.65
75% $CaCO_3$	1800	811	3.39
75% $CaCO_3$ + Mn	11700	1100	2.04
90% $CaCO_3$	714	540	3.12
90% $CaCO_3$ + Mn	8800	2120	1.91

[a]All treatments with manganese added received 5 gm $MnSO_4$ per four inch pot of soil.

The available nutrients in the soil following treatment with various calcium sources at two base saturations are shown in Table 8. The soil analyses made by the spectrographic laboratory were more sensitive than those of the Missouri soil test since in the latter case sufficient dilutions were not made.

Effect of Iron on Manganese Toxicity in Soil Culture

It was stated in the Review of Literature section that high concentrations of soluble manganese in plant tissue are associated with low concentrations of soluble iron. It was further stated that the use of an iron chelate tends to lessen manganese toxicity. To verify these hypotheses, the effects of various iron sources at three application rates were studied on plants grown in soil with and without added manganese.

Calendulas which had been transplanted to 2¼-inch peat pots were potted in steamed soil. The levels of manganese used in the experiment were the natural

TABLE 8 -- AVAILABLE NUTRIENTS IN SOIL FOLLOWING TREATMENT WITH VARIOUS CALCIUM SOURCES AT TWO BASE SATURATIONS.

Treatment	Missouri Soil Test							Spectrographic Lab.		
	O.M.	P_2O_5	K^+	Ca^{++}	Mg^{++}	pH	H^+	Mn^{++}	Fe^{++}	Ca^{++}
	%	Lb./A	Lb./A	Lb./A	Lb./A		m.e.	ppm	ppm	%
Control	1.0	216	280+	5480	220	5.8	1	63	5.40	0.182
Control + Mn[a]	.6	250	280+	5264	1400+	5.9	2	733	3.27	.195
75% CaO	.8	224	256	5480	1400+	6.1	2	104	4.00	.220
75% CaO + Mn	.4	224	280+	5750	1400+	6.0	2	640	3.06	.168
90% CaO	1.9	218	240	4928	1400+	6.5	2	51	2.93	.246
90% Cao + Mn	.8	262	280+	5800+	1400+	6.1	2	666	2.60	.217
75% $CaSO_4$	.6	204	268	5800+	1400+	5.5	2	67	2.13	.219
75% $CaSO_4$ + Mn	.3	236	280+	5800+	1400+	5.5	3	593	4.06	.186
90% $CaSO_4$	.7	172	220	5800+	1400+	5.7	2	140	2.66	.257
90% $CaSO_4$ + Mn	.8	262	280+	5800+	1400+	5.6	3	395	2.70	.220
75% $CaCO_3$	.6	218	280+	5800+	1400+	6.5	1	93	3.27	.237
75% $CaCO_3$ + Mn	.6	250	280+	5800+	1400+	6.1	1	626	8.00	.204
90% $CaCO_3$	.4	216	268	5800+	1400+	6.8	-	19	3.46	.228
90% $CaCO_3$ + Mn	.6	244	280	5800+	1400+	6.6	1	400	5.34	.217

[a]All treatments with manganese added received 5 gm $MnSO_4$ per four inch pot of soil.

level and an addition of five grams manganese sulfate per four-inch clay pot for the high level. Iron was added to the soil as either NaFe EDTA, NaFe DTPA, ALS (Greenz 26) or a mixture of equal parts iron citrate-tartrate. The NaFe EDTA and NaFe DTPA chelates were applied at the rate of 11.3 grams per 100 square feet according to the manufacturer's instructions. ALS was applied at the rate of 34 grams per 100 square feet and the iron citrate-tartrate mixture at the rate of 5.3 and 3.6 grams per 100 square feet, respectively. All plants were given the iron applications as a soil drench. After the plants had grown four weeks, they were harvested and analyzed. Fresh weights were recorded and statistically analyzed as shown in Appendix Table D and Figure 11.

Results of this experiment show a significant decrease in growth of all treatments without added manganese over that of the control. All treatments on plants grown in soils with added manganese showed an increased growth over that of the control except the weekly treatment with ALS. A significant increase in growth was obtained using a bimonthly application of the iron citrate-tartrate mixture on plants grown in soil containing excess manganese. Weekly applications of NaFe DTPA on plants grown in soils containing excess manganese gave a highly significant increase in growth over that of the control.

The concentration of iron and manganese in plant tops varied with the treatments as shown in Table 9. The highest concentration of manganese in the plant tissue was found in the control grown in soil with added manganese. Generally, accumulation of manganese in plant tops was lowest in treatments which received a single iron application. The concentration of iron in the plant tissue did not show this trend.

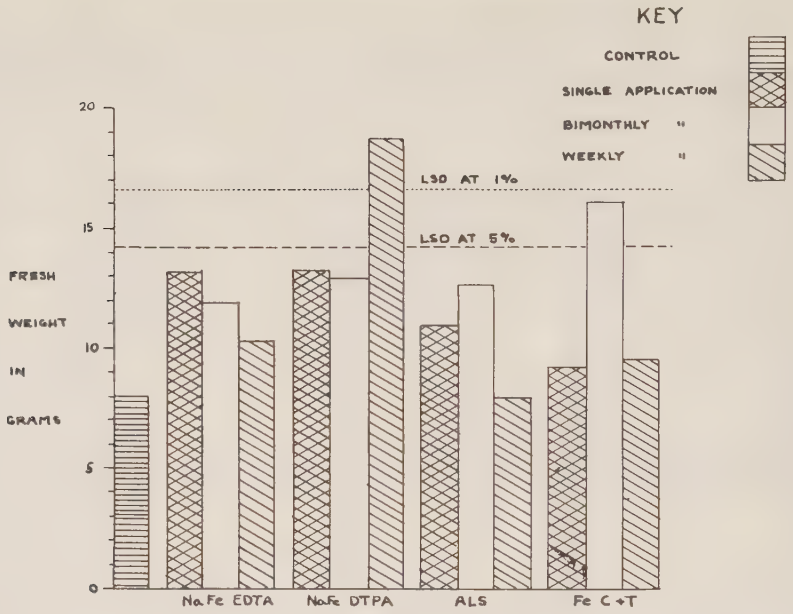

Fig. 11—Fresh weight of tops of calendula grown using various sources of iron with added manganese at five gm $MnSO_4$ per four-inch pot of soil.

DISCUSSION AND PRACTICAL APPLICATION

Symptomatology

Calendula is very susceptible to manganese toxicity, and symptoms are expressed at much lower levels than in most other plants tested. Since symptoms appear within ten to fourteen days, calendula is recommended for use as an indicator or test plant where excess manganese in the soil is suspected.

Carnations tolerated all but the highest levels of manganese and showed toxicity symptoms slowly. This is not surprising since carnations are also known to be tolerant of high soluble salts.

Chrysanthemums were readily affected by excess manganese. However, they are not recommended for use as an indicator plant since the terminal, interveinal chlorosis may also be caused by iron deficiency.

Poinsettias are similar to carnations in that they tolerated high manganese levels. The foliar symptom expression of large brown, scattered necrotic spots is quite definite, however, and unlike any other physiological disease.

Roses gave a terminal chlorosis only at high levels of manganese at which the terminal growth had been suppressed. This condition was found in treatments containing more than six grams $MnSO_4$ per four inch pot of soil or 100

TABLE 9 -- IRON AND MANGANESE CONCENTRATION OF TOPS OF CALENDULA PLANTS GROWN IN SOIL USING VARIOUS SOURCES OF IRON WITH AND WITHOUT ADDED MANGANESE.

Treatment	Application rate	Manganese	Iron
		ppm	ppm
Control	----------	672	390
NaFe EDTA	Single	748	637
NaFe EDTA	Bimonthly	670	741
NaFe EDTA	Weekly	674	1000
NaFe DTPA	Single	510	412
NaFe DTPA	Bimonthly	936	740
NaFe DTPA	Weekly	740	1030
ALS	Single	650	603
ALS	Bimonthly	740	331
ALS	Weekly	847	610
Fe C. & T.	Single	572	439
Fe C. & T.	Bimonthly	614	436
Fe C. & T.	Weekly	750	790
Control + Mn[a]	----------	10100	832
NaFe EDTA + Mn	Single	7320	700
NaFe EDTA + Mn	Bimonthly	8110	545
NaFe EDTA + Mn	Weekly	7430	1010
NaFe DTPA + Mn	Single	7530	385
NaFe DTPA + Mn	Bimonthly	6740	497
NaFe DTPA + Mn	Weekly	7860	498
ALS + Mn	Single	7380	508
ALS + Mn	Bimonthly	8280	490
ALS + Mn	Weekly	7960	579
Fe C. & T. + Mn	Single	8260	389
Fe C. & T. + Mn	Bimonthly	6740	490
Fe C. & T. + Mn	Weekly	8010	441

[a]All treatments with manganese added received 5 gm $MnSO_4$ per four inch pot of soil.

ppm manganese in the nutrient solution. When the chlorosis was eliminated by treatment with iron, the true manganese toxicity symptoms appeared as small black spots scattered over the upper surface of the mature leaves.

Manganese toxicity symptoms in snapdragons were similar to those in calendula, but did not appear rapidly. Snapdragons were not grown in nutrient solution culture, but the plants grown in soil indicate that they are also very sensitive to high manganese levels. Therefore, they should make indicator plants equally as sensitive as calendula.

Stocks were quite tolerant of excess manganese at the levels tested. However, further work should be carried out in both nutrient solution and soil culture to verify this.

Manganese Concentration in Plant Tissue

Manganese is readily absorbed by plants and accumulated in the plant tissue where it often interferes with normal metabolism. Browning of the roots was found to occur with increasing manganese concentrations in the substrate. This

has also been reported by Loew and Sawa (19), and Deatrick (6). There was also a lack of formation of new rootlets which are apparently inhibited by high manganese concentrations in the substrate.

Once in the roots, manganese is transported to the leaves. Kenten and Mann (16) indicate that these accumulations appear to be associated with a browning of the tissues, which may represent a deposition of a higher oxide of manganese with necrosis of the adjacent tissues. Romney and Toth (33) using Mn^{54} reported that it concentrated in the tips of alfalfa leaves and in marginal and interveinal tissue of soybean and tomato leaves. The concentration site in alfalfa could be compared with carnation and that in soybean and tomato with chrysanthemum and calendula. They also reported that numerous small "islands" of Mn^{54} occurred in the interveinal tissue of mature soybean and tomato leaves which is a similar occurrence to that in poinsettia.

Some plants accumulate larger amounts of manganese in the plant tissue than others. Kenten and Mann (16) report that low manganese accumulation obtained in plants grown in high manganese solutions may be due to the rate of reduction of the higher-valency forms being as great as the rate of oxidation of divalent manganese ions. They further state that these results suggest that manganese toxicity is not due in all cases to accumulation of "higher-valency forms of manganese" in the plant tissues.

Plants such as calendula, chysanthemum and snapdragon appear to be very sensitive to high manganese concentrations in the substrate. This might be attributed to a high reduction potential in the plant with a resultant accumulation of manganese in high concentrations. The tolerance of carnation, poinsettia and rose which is probably due to the lower concentrations of manganese accumulated in the tissue might be attributed to an equilibrium between the rate of oxidation and the rate of reduction of manganese.

Effect of Various Deficient Elements Upon Manganese Toxicity

Solutions deficient in a single nutrient decreased growth of chrysanthemum in all treatments. The addition of a toxic concentration of manganese to these solutions further decreased growth except in the treatment deficient in magnesium. This increase in growth was attributed to partial replacement of magnesium by manganese in certain enzyme systems.

It is noted that there is more competition between manganese and cations such as potassium and calcium than with anions such as nitrate or phosphate, as was shown by the greater decreases in growth when the former were deficient. (See Figure 12.)

In plants grown using normal nutrient solution as compared to plants grown with a nutrient solution containing 100 ppm added manganese, all elements tested increased in concentration in the plant tissue with added manganese, with the exception of iron. When plants were grown in solutions deficient in a single nutrient as compared with the same solution containing added manganese, all ele-

Fig. 12—Comparison of symptom expression of chrysanthemum when grown in solution containing 100 ppm added manganese and deficient in potassium as compared to the control.

ments tested increased in concentration in the plant tissue with added manganese with the exception of iron and magnesium. The decreased concentration of magnesium with the addition of manganese to a magnesium deficient solution is not easily explained, since the effect of added manganese in a nutrient solution with a normal amount of magnesium increased the magnesium twofold. Lohnis (22) attributes this to an uptake antagonism between manganese and magnesium. In both cases, the decrease of iron following the addition of manganese might also be attributed to an antagonism.

Effect of Fe:Mn Ratios Upon Manganese Toxicity

The importance of iron and manganese and the apparently conflicting data in the literature concerning the relationships between iron and manganese in plant nutrition make this an interesting problem.

The highly significant decrease in growth of chrysanthemum in treatments using NaFe EDTA or NaFe DTPA at 100 ppm iron was attributed to toxicity of the chelating agent rather than an effect of excess iron. ALS gave a less toxic effect. When iron citrate-tartrate was used, there was no significant decrease in growth over that of the control. Chelated iron sources at one ppm gave no reduction in growth due to chelate toxicity. At one ppm iron, an addition of manganese gave a reduction in plant growth except with NaFe DTPA. This may be attributed to the fact that NaFe DTPA binds iron more strongly than does NaFe

EDTA, especially in a near neutral solution.

At 100 ppm iron, using either NaFe EDTA or NaFe DTPA, there was an increase in growth using 100 ppm manganese over 5 ppm manganese. One might conclude from this that a high concentration of manganese tended to counteract chelate toxicity, instead of the reverse. Low concentrations of chelated iron proved somewhat more beneficial than iron citrate-tartrate in counteracting manganese toxicity and the resultant decreased growth.

The effect of manganese on the uptake of iron was of particular interest since these two micronutrient cations have long been considered to have interdependent relationships in plant nutrition. Increasing the manganese concentration in the substrate which contained one ppm iron considerably increased the amount of chelated iron taken up and translocated. The iron citrate-tartrate treatment gave no significant difference. Conversely, in a substrate containing 100 ppm iron, increasing the manganese concentration decreased the amount of chelated iron taken up and translocated. Again, there was little difference in the iron citrate-tartrate treatment.

Manganese concentration in the tissue was highest at five ppm manganese in the substrate. One explanation would be that at higher manganese levels, there is a deterrent effect upon absorption. Kenten and Mann (16) explain it as follows: "Under conditions of manganese toxicity the rate of oxidation of divalent manganese might be more rapid than the rate of reduction of the oxidation product, thus leading to accumulation of the latter."

The unusual results of this experiment might be attributed to the use of vermiculite as the substrate rather than the usual white quartz sand. It is felt that the use of vermiculite might have permitted better aeration at the roots and decreased reducing conditions. Further work should be carried out to verify this.

Effect of Calcium on Manganese Toxicity in Soil Culture

In decreasing toxic elements in soil, Bear (3) says,

> "Liming the soil raises its pH value thereby causing a lowering of the solubility of manganese and presumably bringing the iron and manganese into better balance in relation to plant needs".

In our experiment, application of various calcium sources to calendula grown in soil containing excess manganese did not alleviate or prevent foliar symptoms of manganese toxicity as has been reported by Hewitt (13). This might be attributed to excessively high amounts of added manganese in the soil. It was apparent in this experiment that at high soil manganese concentrations, toxicity symptoms were enhanced by the addition of calcium as found by Morris and Pierce (29).

The level of exchangeable soil manganese decreased when the base saturation was increased from 75 percent to 90 percent by the use of $CaSO_4$ and $CaCO_3$ thoroughly mixed throughout a high manganese soil. On the other hand, CaO

gave a slight increase in exchangeable soil manganese with increase in base saturation. Concentration of manganese in the plant tissue followed the same trend. The results following addition of $CaSO_4$ and $CaCO_3$ are similar to those reported by Albrecht and Smith (1).

Growth of calendula in the high manganese soils increased with increased addition of CaO and $CaCO_3$. $CaSO_4$ decreased growth at the 90 percent base saturation. This was attributed to the high concentration of sulfate ions, since this same effect was apparent in plants grown under the same treatment without added manganese. It is surprising to note that CaO gave increased growth in a high manganese soil when the level of manganese in the soil and in the plant was increased by addition of CaO. This is apparently due to an interaction of calcium with manganese since the plants grown in soil without added manganese did not show this effect.

It would appear that increasing the pH does not appreciably decrease exchangeable soil manganese unless it is increased to above pH 6.5. See Figure 13, which was extracted from a chart by Truog (39). In the drawing, the influence of reaction and accompanying conditions on the availability of manganese is expressed by the width of the band, i.e. the wider the band, the greater the availability of the manganese.

Effect of Iron on Manganese Toxicity in Soil Culture

The addition of an iron source to a high manganese soil tended to lessen manganese toxicity. Although significant in only a few treatments, the addition of iron to plants grown in soil with added manganese gave increased growth over that of the control. Application of iron sources to calendula grown in soil without added manganese decreased growth in all cases. The greatest decrease in growth was obtained in the iron citrate-tartrate treatment. Possibly this was due to an excess of iron. The greatest decrease in growth using iron chelates was obtained using NaFe EDTA and NaFe DTPA at weekly applications. Typical

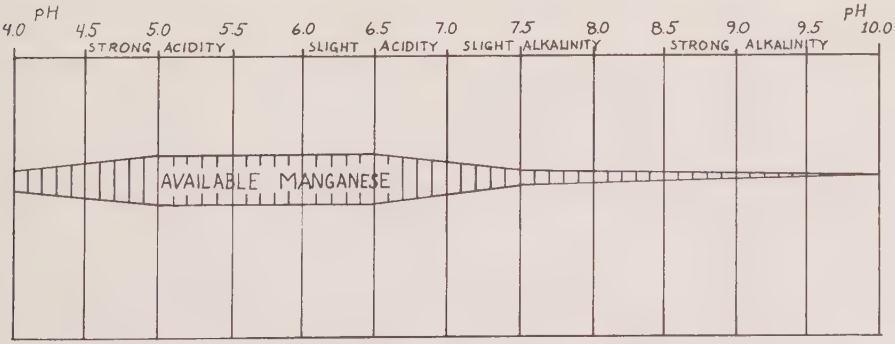

Fig. 13—Chart showing the general trend of the relation of pH to the availability of manganese. (Adapted from Truog.)

chelate toxicity symptoms were observed in some plants when this frequent an application rate was used.

Adding chelated iron to plants grown in soil with added manganese brought a greater increased growth than did the iron citrate-tartrate mixture. ALS, an iron complex (it is not considered a chelate by the manufacturer), gave nearly as good results as the iron citrate-tartrate mixture, though not as good as the two chelate compounds. This is attributed to its rapid decomposition in the soil by soil microorganisms.

Results of this experiment further indicate that there can be no general statement that high concentrations of soluble manganese in plant tissue are associated with low concentrations of soluble iron. In many cases there was an increased concentration of iron in the plant with increased concentrations of manganese. Epstein and Stout (8) state that iron uptake increased with increasing manganese concentration, although the ratio of iron to manganese declined both on the exchange medium and in the liquid phase, thereby indicating that there is no antagonism between manganese and iron. The results as tabulated are in disagreement with Sideris (37) who states that the amount of translocated iron from the roots to the leaves was considerably lower in the cultures supplied with manganese than without. Many of our treatments showed little difference between cultures supplied with or without manganese.

SUMMARY AND CONCLUSIONS

1. Symptomatology of manganese toxicity on selected ornamental plants is described. Foliar symptoms associated with toxic levels of manganese are generally expressed as a terminal, interveinal chlorosis, necrotic spots, or a combination of the two.

2. Either calendula or snapdragon is recommended for use as an indicator or test plant where excess manganese in the soil is suspected.

3. Manganese is readily absorbed by plants and accumulated in the tissues. Amounts of manganese in plant tissue increases with increasing amounts in the substrate.

4. Calendula, chrysanthemum and snapdragon appear to be very sensitive to high manganese concentrations in the substrate, while carnation, poinsettia and rose are more tolerant.

5. Excess manganese decreased growth of plants grown in solution culture deficient in a single nutrient in all cases except magnesium, which was attributed to its partial replacement by manganese in certain enzyme systems.

6. The concentration of magnesium and iron in plant tissue decreased when manganese was added to plants grown in a nutrient solution deficient in these elements.

7. Of the ratios tested, an Fe:Mn ratio of 1:5 in ppm gave the best growth. Low concentrations of chelated iron (1 ppm) proved somewhat more beneficial than high concentrations in counteracting manganese toxicity in solution cul-

ture.

8. Applying various calcium sources to plants grown in soil containing excess manganese did not alleviate or prevent foliar symptoms of manganese toxicity.

9. Increasing the pH of the soil by addition of calcium did not appreciably decrease exchangeable soil manganese in these experiments.

10. Adding iron to plants grown in a high manganese soil increased growth. The most effective rate of application depended upon the iron source.

BIBLIOGRAPHY

1. Albrecht, W. and Smith, N. C. 1941. Calcium and Phosphorous as they influence Manganese in forage crops. *Bulletin of Torrey Botanical Club* 68:372-380.
2. Baxter, P. 1955. Manganese Excess in Peach Trees. *Jour. Austr. Inst. Agr. Sci.* 21:170-172.
3. Bear, F. E. 1957. "Toxic Elements in Soil," *The Yearbook of Agriculture.* pp. 165-171.
4. Brenchley, W. E. 1914. Effect of manganese compounds In inorganic plant poisons and stimulants, pp 78-92. *Cambridge Agr. Monographs.*
5. Carlson, C. S. and Olson, R. V. 1951. Iron-manganese ratios in nutrient solutions in relation to the chlorosis of sorghum plants. *Soil Sci. Soc. Amer. Proc.* 15:251-254.
6. Deatrick, E. P. 1917. The effect of manganese compounds of soils and plants. Ph.D. Thesis, *Cornell University, Ithaca,* N. Y.
7. Dinius, R. H. 1953. Determination of trace elements in representative Missouri soils. Master's Thesis, *University of Missouri, Columbia,* Mo.
8. Epstein, E. and Stout, P. R. 1951. The micronutrient cations iron, manganese, zinc, and copper: Their uptake by plants from the absorbed state. *Soil Sci.* 72:47-65.
9. Forsee W. T., Jr. 1954. Conditions affecting manganese in organic soils. *Soil Sci. Proc.* 18:475.
10. Fujimoto, C. K. and Sherman, G. D. 1948. Manganese availability as influenced by steam sterilization of soils. *Jour. Amer. Soc. Agron.* 40:527-534.
11. Graham, E. R. 1950. Testing Missouri Soils. *Mo. Agr. Expt. Sta. Circ.* 345.
12. Hale, J. B. and Heintze, S. G. 1946. Manganese toxicity affecting crops on acid soils. *Nature* 157:554-559.
13. Hewitt, E. J. 1945. The resolution of the factors in soil acidity. *Ann. Rep. Long Ashton Res. Sta.* pp 51-60.
14. Hoagland, D. R. and Arnon, D. I. 1950. The water-culture method for growing plants without soil. *Calif. Agr. Expt. Sta. Circ.* 347.
15. Hopkins, R. F., Pagan, V., and Silva, F. J. R. 1944. Iron and manganese in relation to plant growth and its importance in Puerto Rico. *Jour. Agr.*

Univ. Puerto Rico 28:43-101

16. Kenten, R. H. and Mann, P. J. G. 1957. Manganese oxidation in the pea plant *(Pisum sativum L.)* grown under conditions of manganese toxicity. *Biochem. Jour.* 65(1):179-185.
17. Leeper, G. W. 1935. Manganese deficiency of cereals, plot experiments and a new hypothesis. *Proc. Roy. Soc. Victoria* 47(II):225-261.
18. Leeper, G. W. 1947. The forms and reactions of manganese in the soil. *Soil Sci.* 63:79-94.
19. Loew, O. and Sawa, S. 1902-03. On the action of manganese compounds on plants. *Tokyo Imp. Univ., Col. Agr. Bul.* 5:161-172.
20. Lohnis, M. P. 1950. Manganese toxicity in beans. *Soils and Fert.* 13:302.
21. Lohnis, M. P. 1951. Manganese toxicity in field and market garden crops. *Plant and Soil* 3:193-221.
22. Lohnis, M. P. 1954. Influence of magnesium on the uptake of manganese. *Commun. 8th Intern. Botan. Congr.,* Sect. 11/12, pp. 83-85. (Paris, France)
23. McCool, M. M. 1934. Effects of various factors on the soluble manganese in soils. *Contr. Boyce Thompson Inst.,* 6:147-164.
24. McCool, M. M. 1935. Effect of light intensity on the manganese content of plants. *Contr. Boyce Thompson Inst.* 7:427-437.
25. McHargue, J. S. 1922. The role of manganese in plants. *Jour. Amer. Chem. Soc.* 44:592-598.
26. Mederski, J. J. and Wilson, J. H. 1955. Effect of temperature on manganese absorption by soybean plants. *Soil Sci. Soc. Amer. Proc.* 19:461-464.
27. Millikan, C. R. 1942. Studies on soil conditions in relation to root rot of cereals. *Proc. Royal Soc. Victoria* 54:145-195.
28. Morris, H. D. 1948. The soluble manganese content on acid soils and its relation to the growth and manganese content of sweet clover and lespedeza. *Soil Sci. Soc. Amer. Proc.* 13:362-371.
29. Morris, H. D. and Pierce, W. H. 1947. The effect of calcium, phosphorous, and iron on the tolerance of lespedeza to manganese toxicity in culture solutions. *Soil Sci. Soc. Amer. Proc.* 12:382-386.
30. Mulder, E. G. and Gerretsen, F. C. 1952. Soil manganese in relation to plant growth. *Advances in Agronomy.* New York, Academic Press Inc. 4:231-277.
31. Ozaki, C. T. 1953. Factors influencing the toxicity of manganese in tomatoes following the steaming of certain Ohio greenhouse soils. Ph.D. Thesis, *Ohio State University, Columbus,* Ohio.
32. Piper, C. S. 1931. The availability of manganese in the soil. *Jour. Agr. Sci.* 21:762-779.
33. Romney, E. M. and Toth, S. J. 1954. Plant and soil studies with radioactive manganese. *Soil Sci.* 77:107-117.
34. Sandell, E. B. 1914. *Colorimetric determination of trace metals.* New York, Interscience Publisher Inc. pp. 312-314.

35. Sherman, G. D., McHargue, J. S. and Hodgkiss, W. S. 1942. Determination of active manganese in soil. *Soil Sci.* 54:(No. 4) 253-257.
36. Sherman, G. D. and Fujimoto, C. K. 1946. The effect of use of lime, soil fumigants and mulch on the solubility of manganese on Hawaiian soils. *Soil Sci. Soc. Amer. Proc.* 4:206-210.
37. Sideris, C. P. 1950. Manganese interference in the absorption and translocation of radioactive iron (Fe^{59}) in *Ananas comosus* (L) Merr. *Plant Physiol.* 25:307-321.
38. Somers, I. I. and Shive, J. W. 1942. The iron-manganese relation in plant metabolism. *Plant Physiol.* 17:582-602.
39. Truog, E. 1943-47. "The Liming of Soils," *The Yearbook of Agriculture.* pp. 566-576.
40. Twyman, E. S. 1946. The Fe/Mn balance and its effect on the growth and development of plants. *New Phytol.* 45:18-24.
41. Wallace, Arthur. 1956. *Symposium on the use of metal chelates in plant nutrition.* Palo Alto, The National Press. pp 80.
42. Wallace, T. and Hewitt, E. J. 1946. Problems of iron deficiency and the interrelationship of mineral elements in iron nutrition. *Jour. Pomol. and Hort. Sci.* 22:153-161.
43. Weinstein, L. H., Purvis, E. R., Meiss, A. N., and Uhler, P. L. 1954. Chelates—absorption and translocation of ethylenediamine tetraacetic acid by sunflower plants. *Jour. Agr. Food Chem.* 2:421-425.
44. Willis, L. G. 1932. The effect of liming soils on the availability of manganese and iron. *Jour. Amer. Soc. Agron.* 24:716-726.

APPENDIX TABLES

APPENDIX TABLE A -- FRESH WEIGHTS OF CHRYSANTHEMUMS GROWN IN MINERAL DEFICIENT NUTRIENT SOLUTIONS WITH AND WITHOUT EXCESS MANGANESE.

Treatment	Fresh weight in grams per plant					Mean
	1	2	3	4	5	
Control	64.0	72.8	60.1	66.9	63.7	65.5
Minus N	20.7	17.4	14.9	16.0	14.4	16.7**
Minus P	13.5	10.4	17.2	8.9	12.7	12.5**
Minus K	36.0	26.1	37.1	23.8	34.6	31.5**
Minus Ca	13.0	10.4	14.9	26.8	14.8	16.0**
Minus Mg	20.0	14.0	13.7	19.9	24.6	18.4**
Minus S	45.7	42.0	40.1	41.3	43.4	42.5**
Minus Fe	58.0	44.0	40.0	47.2	50.9	48.0**
LSD at 1%						8.5
Control + Mn[a]	55.4	51.2	48.5	55.0	47.8	51.6
Minus N + Mn	15.3	16.9	10.3	11.7	13.9	13.6**
Minus P + Mn	10.0	13.0	7.7	11.3	8.1	10.0**
Minus K + Mn	13.3	8.8	8.4	14.3	9.3	10.8**
Minus Ca + Mn	6.4	8.0	4.8	6.6	7.2	6.6**
Minus Mg + Mn	21.5	30.0	17.5	17.2	26.5	22.5**
Minus S + Mn	34.7	28.3	20.0	25.8	23.2	26.4**
Minus Fe + Mn	25.2	30.1	43.3	32.4	27.8	31.8**
LSD at 1%						7.5

[a]All treatments with manganese added had 100 ppm manganese in the solution.
*Significance exceeds 5% level.
**Significance exceeds 1% level.